Effect of implant stiffness on spinal growth in the pig spine

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Abstract

Introduction
According to the 'vicious cycle' hypothesis proposed by Dr Stokes, sensitivity to load has been implicated in the progression of spinal deformity during growth due to the reaction of vertebrae to mechanical loads on their growth plate. Mechanical loads on the vertebrae are altered by the mechanical stiffness of the spinal implant. Unfortunately, the relationship between the implant stiffness and the modulation of spinal growth is not quantified. In vitro and finite element studies involving multiple pig spines and segments (T1–T4, T5–T8, and T9–T12) were used. Springs of varying length (320 N/m stiffness) and a metal link (64.5 × 106 N/m stiffness) were attached to adjacent vertebrae and the spines distracted to model growth. This review aims to analyse the study investigating the effect of implant stiffness on this growth using experimental and finite element techniques.

Discussion
It is shown that the addition of an implant to the spinal column will increase the stiffness of the spine. Furthermore, as the stiffness increases, the distraction of the spine decreases. In addition, asymmetric placement of the implant leads to rotation of the spine segment during distraction.

Conclusion
Spinal devices with different mechanical properties yield variable stiffness of the spine segments, as well as displacement and rotations, which will further affect the longitudinal growth of the spine.

Introduction
Much debate and research in the study of scoliosis in the past decade has focused on the 'vicious cycle' hypothesis. This hypothesis maintains that loads on the spine are asymmetric and involved in curve progression through changes in bone and disc growth and hence to vertebral body and disc wedging. Axial and longitudinal loading of vertebral bodies has been shown to modulate the growth rate of the body relative to the control vertebrae. Growth is modulated by increased compressive forces. As mechanical loads on the vertebrae are altered by the mechanical stiffness of the spinal implant, it is possible that the implant stiffness will modulate growth.

Thus, the appropriate goal of surgical treatment for early onset scoliosis is to correct the progression of the spinal curvature while allowing growth of the spine and its adjacent structures. This has led to the introduction of fusionless implant devices, multiple level staples, vertical expanding prosthesis and a dual growing rod technique. In a study using the dual growing rod technique, Akbarnia et al. reported an improvement of scoliosis from 82° to 38°, while T1-S1 length increased from 23 cm to 32.7 cm at the last follow-up. Unlike traditional instrumentalations, such as Cotrel–Dubousset, which are very rigid and affect spine growth, these fusionless devices are more compliant. Nevertheless, the introduction of any implant to the spinal column will alter the mechanical behaviour of the spinal column and affect spinal growth.

Glos et al. investigated the in vivo effect of a staple-like implant on the baseline disc stress in a pig spine. It was found that the implant does affect the stress increasing the mean stress between 0.1 and 0.2 MPa. Unfortunately, the authors performed the study for only one type of implant, so the relationship between growth modulation and the variation of implant stiffness is unknown. Thus, a study was undertaken to investigate different implant stiffness, spinal linear and angular displacements using experimental and finite element techniques. The aim of this review is to assess this study and the results obtained.

Implant stiffness
Spinal implants are essentially spring like. Assuming that these devices are properly anchored, their resistance to growth increases with growth. Furthermore, the level of resistance is dictated by the mechanical stiffness of the device. As they are constructed from metal (titanium and stainless steel), their mechanical stiffness and hence resistance to growth is large.

In order to investigate the impact of a fusionless device, a titanium link was developed (Dept. of Orthopaedic Surgery, Medical College of WI, Milwaukee, WI). The link is a plate with two oval-shaped holes, wherein the vertebral bones are attached via bone screws. As spinal growth progresses,
the screws are able to move within these holes, so outside of frictional resistance, there is very little resistance to growth. Based on the relative positions of the holes, their size and the diameters of the bone screws, the holes allow the spine to move freely up to a displacement of 1.765 mm. At this distraction, the screws bind and the instrumentation behaves as a rigid linear bar having a stiffness of 64,533 N/mm. Thus, the behaviour of the plate is non-linear, with little to no resistance for a distraction (growth) less than 1.765 mm and linear thereafter with a stiffness of 64,533 N/mm.

In addition, long and short springs were used in this study. These springs had the same spring constant (0.320 N/mm). Compared to the plate, the stiffness of these springs is quite small so the plate is more rigid than the spring. As the stiffness of the spring and plate varies, the effect of implant stiffness on spinal growth may be easily investigated by comparing the behaviour of the spine with and without these devices. In subsequent sections of this paper, in vitro and finite element studies are discussed that examine this effect.

**In vitro study**

Eight spine segments from three different female pigs weighing 60–90 lb pig spines were subjected to a continuous tensile force that modelled growth. The thoracic segment of each pig spine was divided into three segments—T1–T4, T5–T8 and T9–T12. Each cadaver pig spine segment was thawed to room temperature before testing. Titanium screws were inserted into the centre of two adjacent vertebral bodies. Both ends of the specimen were set in a PMMA block and screwed to specially designed fixtures.

In order to mimic the mechanical forces during growth, a distractive load (0–400 N) was applied using an Alliance™ RT/50 (MTS, Eden Prairie, MN) load frame. The resulting spinal extension between adjacent vertebrae was recorded using an extensometer (Figure 1). The pull-out of the spine from a PMMA block equated to spine failure at which point the test was stopped.

The control test measured displacement between the screws without any implant. The spring test involved linking the screws with either the long or short spring. The plate test consisted of connecting the screws with the metal plate link.

**Finite element studies**

As shown in Figure 2, a finite element model of two vertebrae (Young’s modulus: 40.51 MPa, Poisson ratio: 0.29), one disc (Young’s modulus: 1.93 MPa, Poisson ratio: 0.45) and two titanium screws (Young’s modulus: 110 GPa, Poisson ratio: 0.33) was developed using Patran® and Nastran® (MSC Software, Santa Ana, CA). Material properties for the spine segments were obtained experimentally from nine pig spine segments. One screw was inserted in each vertebral body. The vertebral bodies in vitro and finite element studies are discussed that examine this effect.

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**Figure 1:** A spine segment loaded with a tensile load. An extensometer is used to measure the extension.

**Figure 2:** Meshed finite element model of the vertebrae, disc screws and spring. The inset shows the relative sizes of the vertebrae and disc.
and discs were meshed using 10 node tetrahedral elements. In order to model the relative growth of the spine, the base of the spine segments was fixed in all directions and rotations. Simulations were carried out by varying the distractive load from 5 to 100 N.

In the simulations, the stiffness of the linear springs was varied from 0 N/mm (uninstrumented spine) to $10 \times 10^5$ N/mm (very rigid instrumentation). This range included the short and long springs used in the *in vitro* test. The large range of spring stiffness provided results that would have been impractical to obtain in the *in vitro* tests. Spring elements spanned the disc and modelled the instrumentation. Linear properties were assigned to these elements in order to model the long and short springs. On the other hand, to model the plate, non-linear spring elements (Nastran® CBush) were used with the stiffness of zero for displacements less than 1.765 mm and 64,533 N/mm for displacements thereafter.

Similar to the material properties of the spine segments, the geometry of the spine was obtained from nine spine segments using the X-rays\(^{10}\). Average values were used in the model (vertebrae height: 15.62 mm, anterior posterior diameter: 10.75 mm, medial/lateral diameter: 16.62 mm and disc space: 2.25 mm).

The finite element model was constructed and analysed using the recommendations in Viceconti\(^{11}\). As the finite element analysis was concerned with the numerical modelling of pig spines, the finite element results were validated via the *in vitro* tests.

**Discussion**

The authors have referenced some of their own studies in this review. The protocols of these studies have been approved by the relevant ethics committees related to the institution in which they were performed. Animal care was in accordance with the institution guidelines.

**In vitro study**

We show in Figure 3 typical curves obtained for a spine with and without implants. For the sake of brevity, we plot one example here, but similar results were obtained for much higher load ranges. By employing the method of least-squares fit, the load displacement curves are used to generate the stiffness of the spine segment for each case considered. In Table 1, we list the spine stiffness for various segments and the load range 0 to 110 N.

**Finite element studies**

Figure 4 shows a typical displacement FEA result. This result is for a traditional instrumentation with stiffness of 100 N/mm and an applied load of 100 N. Note the reduction in the displacement (34.55%) of the side with the attached spring compared to the side without the spring and the lateral bending of the spine in the coronal plane.

For the sake of brevity, the FEA results for the plate are not shown. However, at an applied load of 100 N, the displacement of the instrumented side of the spine is 0.062268 mm. On comparison with the result for the 100 N/mm spring analyses (Figure 4), we find that the use of the plate rather than the spring leads to an additional 8.13% reduction in the spine displacement. This is expected because the plate is stiffer than this particular spring.

Figure 5 shows a plot of the angle of the upper vertebra (with respect to the horizontal) as a function of spring stiffness. The rotation increases with increasing stiffness of the instrumentation until it reaches an asymptotic value.

The results from this study indicate that the addition of an implant

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Table 1: Spine stiffness for various spine segments and all load ranges (0–110 N)

<table>
<thead>
<tr>
<th>Test</th>
<th>Segment</th>
<th>Spine stiffness (N/m)</th>
<th>Load range (N)</th>
<th>Average spine stiffness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>T1T4 PIG A</td>
<td>11,761</td>
<td>14–18</td>
<td>31,429</td>
</tr>
<tr>
<td></td>
<td>T5T8 PIG C</td>
<td>75,571</td>
<td>75–110</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T9T12 PIG B</td>
<td>6955</td>
<td>0–10</td>
<td></td>
</tr>
<tr>
<td>Plate</td>
<td>T1T4 PIG A</td>
<td>10,151</td>
<td>14.5–19</td>
<td>59,587</td>
</tr>
<tr>
<td></td>
<td>T5T8 PIG C</td>
<td>114,920</td>
<td>20–35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T9T12 PIG B</td>
<td>53,691</td>
<td>0–10</td>
<td></td>
</tr>
<tr>
<td>Spring (short)</td>
<td>T5T8 PIG C</td>
<td>80,076</td>
<td>25–40</td>
<td>46,544</td>
</tr>
<tr>
<td></td>
<td>T9T12 PIG B</td>
<td>13,011</td>
<td>0–10</td>
<td></td>
</tr>
<tr>
<td>Spring (long)</td>
<td>T1T4 PIG A</td>
<td>10,965</td>
<td>3–10</td>
<td>10,965</td>
</tr>
</tbody>
</table>
where there is considerable extension of the spine. This can be seen in Table 1. Thus, as the link becomes more rigid, the spine becomes stiffer.

In addition, for the plate test, although not apparent in Figure 3 (due to the scaling of the plot) the stiffness of the spine at low values of distraction is much less than at higher values and is of the order of the value obtained in the control test. This is because at low values of distraction, the plate provides very little resistance to the distraction; hence, the spine has stiffness nearly equivalent to an uninstrumented spine. However, the region of distraction over which this is true is quite small as the plate allows little free movement of the spine before the screws bind in the oval holes and the resistance to distraction increases dramatically.

A comparison of the spring and plate tests indicates that in general, the spine is stiffer with the addition of the plate than the spring. This is because the plate is a rigid link and allows very little displacement compared to a spring. It is interesting to note that the stiffness of the spring affects the stiffness of the spine, as one would expect. In our *in vitro* tests, we examined both short and long springs. The variation in the length of the springs allowed us to change the initial stretch of the springs. Thus, a short spring that was stretched more than a long spring would apply a larger resistive force (see Table 1, long spring: 10,965 N/m compared to the average of the short spring: 46,543 N/m). This implies that the more rigid the implant is, the stiffer the spine and hence the greater the resistance to growth.

From the point of view of mechanics, the vertebrae and disc are essentially springs in a series, which are in parallel with the stiffness of the instrumentation. For low spring (instrumentation) stiffness, the spine stiffness is greater so the resistance to growth in the spine will increase the stiffness of the spine, which will affect the extension of the spine and hence hinder growth in the spine. The plate had oval holes that allowed for some motion. At small loads, there is less effect on the spine than there would be in higher loads.

**Figure 4:** Reduction of the spine displacement for spring stiffness of 100 N/mm and distraction force of 100 N. Displacements are in mm.

**Figure 5:** Rotation of the vertebrae in the coronal plane with spring stiffness.

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is the case in Figure 3. One would expect that at high spring stiffness, the stiffness of the instrumentation would dominate and the effect of the instrumentation would go to zero, yet this is not the case.

In order to see what is happening at higher values of instrumentation stiffness, we must recognize that the spring force is asymmetric to the longitudinal axis of the spine. At low spring stiffness, the moment generated by the spring is negligible as the force is very small. However, at high spring stiffness values, this moment is quite large and dominates the behaviour of the spine. Thus, at higher spring stiffness, the results are primarily due to a rotation of the spine and not linear translation under the applied tensile load.

Screws that are farther apart span more of the spine segment. The initial spring force is greater, hence the results in Figure 5.

In this figure, we see that for the same applied tensile force of 100 N, the analysis shows that for the plate the rotation is −1.43° whereas for the 100 N/mm spring, it is −1.22°. Though the stiffness of the plate is non-linear, the rotation is −1.43° whereas for the 100 N/mm spring, it is −1.22°. Though the stiffness of the instrumentation is non-linear, the results are primarily due to a rotation of the spine.

In this study, the effect of instrumentation stiffness was non-linear, which means that the results are primarily due to a rotation of the spine and not linear translation under the applied tensile load.

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References